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TECHNICAL MEMORANDUM

OPTICAL BEACONS FOR ACQUISITION AND TRACKING OF S191 TARGETS DURING NIGHT-SIDE PASSES

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ABSTRACT

Recent changes in Skylab system constraints now permit occasional operation of the Earth Resources Experiment Package (EREP) on the dark side of the earth. Although most IR observations are planned for the sunlit side, there are applications for night-side observations. Geothermal activity, for example, is more easily measured at night in the absence of solar heating. Experiment S191 - Infrared Spectrometer makes single point measurements and must be aimed by an astronaut. If specific small targets are to be located at night, some type of visible beacon on the ground will be required.

A concept for a simple, low-cost, portable beacon is defined: a narrow light beam from a searchlight or other high-intensity source is swung back and forth in a vertical plane nearly coincident with the spacecraft's orbital plane to provide an apparently flashing beacon as viewed from orbit. The width of the light beam permits it to be seen from the Orbital Assembly if the searchlight is positioned within a few miles of the ground track.

Expressions are derived for the luminous intensity required for visibility from orbit. It is shown that commonly available searchlights have more than adequate candlepower to assure visibility through clear air.

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TECHNICAL MEMORANDUM

1.0 Introduction

Until recently, use of the local-vertical spacecraft attitude for EREP passes was restricted to sunlit portions of the Skylab orbit. Several weeks ago, however, MSFC approved an MSC Engineering Design Change Request broadening the EREP operating regime to include passes over the night side of the earth as well as the sunlit side (Reference 1).

With the exception of Experiment S191 - "Infrared Spectrometer", EREP experiments can be operated over the earth's night-time hemisphere with no more difficulty than over the sunlit hemisphere. S191 differs from the other EREP experiments in that it has been designed to enable a flight crewman to visually acquire target regions on the earth, to manually track targets following acquisition, and to monitor tracking while data is being recorded.*

The ability of an astronaut to acquire an S191 target on the dark side of the earth depends largely on the target's size and the availability of visible, nearby landmarks.

If the area of the target region is sufficiently large, it will not be necessary for the S191 operator to visually acquire the target at all. Activating the experiment at a pre-determined time would be sufficient to insure that the instrument's field-of-view is on target; appropriate activation times could be calculated at the Mission Control Center from the Skylab's ephemeris and relayed to the spacecraft in advance by voice or teletype. The accuracy with which activation times can be predicted will determine the size of target regions for which this operating mode is usable.

*S191 targets may be as small as one nautical mile in diameter (Reference 2).

Small targets would, however, require visual acquisition. Targets that are not excessively small and are fortuitously located near identifiable landmarks may be "acquired" indirectly by offsetting the S191 line-of-sight from the visible marks; the lights of nearby towns or cities might serve as landmarks from which offsetting could be accomplished with satisfactory accuracy. Small regions not located near visible landmarks will not be usable as S191 night-time targets unless a means is developed for locating them from orbit.

It appears that the simplest, and very likely cheapest, way to mark small target regions for night-time S191 observations is to provide an optical beacon bright enough to be seen from the spacecraft. This memorandum briefly examines the need for such a beacon, defines the optical characteristics required for a beacon, and compares them with the capabilities of a readily available light source to demonstrate the feasibility of the optical beacon concept.

2.0 Will There Be S191 Targets That Require Optical Beacons?

Principal Investigators (PI's) for EREP experiments have not yet been selected and are not likely to be chosen until the latter part of this year. EREP targets and viewing conditions required for data-taking will not be known definitely until PI's have been named. It is therefore not possible to determine at this time whether S191 investigations will require night-time observations. Potential night-time applications for S191 do, however, exist.

Aerial photographs of the ground taken at night in the wavelength band of emitted thermal radiation are known to exhibit markedly different characteristics from those taken during the day; the effects of solar heating create diurnal variations in the infrared images.

Investigations of southern Californian terrain from aircraft have indicated that pre-dawn infrared imagery in the 8 to 13 micron band can in some cases be correlated with the specific gravities of surface materials, whereas images obtained during daylight hours are largely determined by topography due to differential warming of ground surfaces oriented at various angles to the sun (Reference 3). Infrared mapping of volcanic regions can be performed with greater accuracy at night than during the day since bright solar irradiation can result in "hot spots" that are difficult to distinguish from those caused by underlying volcanic activity (Reference 4). Both daytime and night-time aerial infrared imaging have been shown to be useful in hydrological investigations of drainage patterns and networks: temperature differences between water and surrounding terrain create patterns visible even in the presence of overhanging foliage (Reference 5).

In view of these and other possible applications, it is reasonable to anticipate that EREP operations may include the collection of infrared images over portions of the earth's dark hemisphere. Experiment S192 - "Multispectral Scanner" provides an imaging capability in spectral bands covering the atmospheric window for earth-emitted IR radiation. Data collected simultaneously by the S191 spectrometer from small areas within the S192 field-of-view could provide atmospheric data that would permit S192 images to be corrected for atmospheric effects (Reference 6). Obtaining ground-truth data for comparison with S191 observations requires accurate pointing of the spectrometer's field-of-view to assure that orbital and ground-based data are collected from the same location. Precise pointing of Experiment S191 requires visual acquisition of the target by the astronaut operating the experiment's Viewfinder/ Tracking System (V/TS). In most instances, such visual acquisition during night passes will be possible only if a beacon visible from orbit is in place at the target site to serve as a target marker.

In addition to providing support for the Multi-spectral Scanner, the Infrared Spectrometer can itself be used for independent investigations that may benefit from performance over the dark side of the earth. For example, spectral signatures in emitted infrared wavelengths can to some extent be correlated with the mineralogical composition of certain rock types based on their silicate composition (Reference 7).

3.0 Overall Concept for an S191 Night-Time Target Marker

An optical beacon suitable for supporting S191 night-time operations should have the following characteristics: (1) high visibility from orbit; (2) a unique appearance to assure positive identification; (3) portability to permit use of one beacon at more than one site; and, (4) low cost.

Cost will be minimized if an existing, readily available light source can be used. Visibility against the dark earth from orbital altitudes will obviously require a beacon of high luminous intensity: this immediately suggests lamps in the "searchlight" category. Transportable, truck-mounted searchlights are commonplace. The narrow beam of a searchlight offers the advantage of efficiency in concentrating its light in a given direction. If the beam is held stationary, however, its narrowness becomes a liability: an observer in the Workshop flying through the beam would see it, if he saw it at all, as a single, brief flash of light which would not permit target tracking.

Fortunately, this liability can be converted to an advantage. A flashing light bright enough to be seen will be noticed more readily by an observer than a steady light. A flashing light also provides a positive means of identification from the known rate at which it flashes. A steady searchlight beam can be made to appear from orbit as a flashing beacon by repeatedly swinging the beam back and forth in a vertical plane coincident with the Workshop's orbital plane when the spacecraft is above the searchlight's horizon.

For a given spacecraft pass over a particular point on the ground, the direction from which the spacecraft will approach the site can be calculated in advance to permit the light beam to be properly aligned. Throughout the flight all spacecraft passes over a given site will approach from one of only two possible directions, determined by orbital altitude and inclination. For accurate alignment of the searchlight beam, it would be necessary to "survey in" the light's base at every target site to which it is assigned. The remainder of this memorandum defines the luminous intensity required for an S191 optical beacon and compares required intensities with available searchlight capabilities.

4.0 Luminous Intensity Required For Visibility of an Optical Beacon From Orbit

The visibility from orbit of a searchlight located on the ground depends upon the luminous intensity of the searchlight beam, the distance between spacecraft and beacon, the physiological brightness detection-threshold of the observer, the effects of atmospheric attenuation of the light beam, the apparent flash duration as seen by the observer, and the effects of the S191 Viewfinder/Tracking System's optics.

4.1 Photometric Parameters and Point Sources

Before proceeding further it will be convenient to list definitions for, and relationships among, photometric parameters that will be used in succeeding sections of this memorandum. Systems of units employed in photometry are large in number and proverbially confusing. (For example, it is not immediately obvious that "lamberts" and "foot-lamberts" are both measures of the same photometric parameter, luminance.) In the interests of simplicity, all photometric units used in this study will be expressed in terms of three basic quantities: power measured in lumens, length measured in meters, and solid angles measured in steradians.

Energy in the visible spectrum radiated per unit time from a surface is defined as luminous flux, which can be measured in lumens. The luminous flux per unit solid angle radiated in a given direction away from a surface element is designated luminous intensity (I), measured in lumens/steradian. The photometric brightness or luminance (L) of a surface element is the luminous intensity of that element in a given direction, per unit area of the element; luminance is therefore measured in lumens/(steradian-meter^2).*

If a surface having a uniform photometric brightness or luminance L_1 is compared with another surface of uniform luminance L_2, the contrast (C) between the two surfaces is defined as $(L_1 - L_2)/L_2$, where $L_1 \geqslant L_2$. Threshold contrast (C_T) is the lowest value of contrast that an observer with normal vision can distinguish from a contrast of zero with a given probability of being correct.*

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*References 8, 9, and 10.

A luminous source is defined as a point source for observers sufficiently far away in a given direction that the product of threshold contrast and solid angle (Ω) subtended by the object is constant with respect to changes in the distance between source and observer.* This definition, known as Ricco's Law, simply states that for a point source,**

$$\Omega C_T = \text{constant} \equiv K, \text{ or}$$

$$\left(\frac{L_O - L_B}{L_B}\right)\Omega = K \ , \tag{4.1-1}$$

where L_O is the threshold luminance of the "point source" viewed against a background luminance L_B from a given distance.

Illuminance (E) is the luminous flux per unit cross-sectional area of a light beam, measured in lumens/meter^2. For a point source of uniform intensity I radiating into a solid angle ω, the luminous flux into ω is $I\omega$; the illuminance within ω at a distance ρ from the source is the ratio of luminous flux to the area (A) subtended by ω on a sphere of radius ρ centered at the source. From the definition of a steradian,*** $A = \omega\rho^2$. Thus, for a point source, $E=I\omega/(\omega\rho^2)$, or

$$E = \frac{I}{\rho^2} \ . \tag{4.1-2}$$

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*The maximum angular diameter of a luminous object that will satisfy the definition of a point source varies with background luminance. For example, objects subtending less than $\sim$3.3 arcmin can be considered point sources when viewed from orbit against the night-time, full-moonlit earth whose luminance is $\sim$0.0238 lumens/(steradian-meter^2). Under such conditions, objects located on the earth's surface are "point sources" in relation to an observer directly overhead at orbital altitude (h = 235. nautical miles) if the objects are less than 420. meters in diameter.

**Reference 8.

***One steradian subtends a solid angle that intercepts an area R^2 on a sphere of radius R centered at the point from which the solid angle is measured.

For a plane object of area a viewed from a direction normal to a, the solid angle Ω subtended by the object at a distance ρ is a/ρ^2, provided $\rho^2 >> a$. If the object is luminous and a point source in relation to the observer, the following equation, obtained by substituting $\Omega = a/\rho^2$ into Equation (4.1-1), is applicable:

$$L_o a = L_B (a + K\rho^2) \quad . \tag{4.1-3}$$

For ρ^2 sufficiently great in comparison with a,

$$L_o \, a \approx K \, L_B \, \rho^2 \quad . \tag{4.1-4}$$

If the threshold luminance L_o is uniform over area a, the threshold intensity ($\hat{I}_\rho$) of the point source for the observer at distance ρ normal to the plane of a is

$$\hat{I}_\rho = L_o a \quad . \tag{4.1-5}$$

Combining relations (4.1-4) and (4.1-5) yields

$$\hat{I}_\rho \propto L_B \rho^2 \quad . \tag{4.1-6}$$

The threshold illuminance at the observer's location due to the point source is

$$\hat{E} \propto L_B \, , \tag{4.1-7}$$

which follows from relations (4.1-2) and (4.1-6). Expression (4.1-7) states that for a point source, threshold illuminance is independent of the distance between source and observer.

4.2 Visibility Criterion

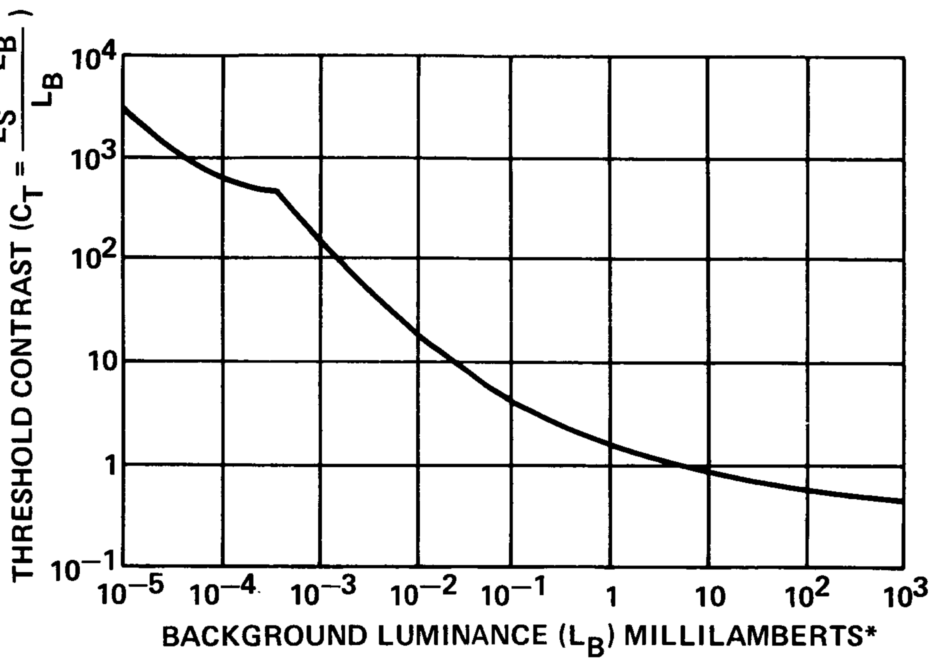
The retinal response to light from a point source is determined primarily by the luminous flux received from the source, the background luminance against which the source is viewed, and the level of adaptation of the eye at the time of viewing. The level of adaptation at an instant of time is determined by the history of light impulses to which the eye has been exposed during several minutes prior to that time. Exposure to an unchanging visual field results in an equilibrium adaptation to the photometric brightness of that field. For the purposes of this study, it will be assumed that the S191 operator's eyes are adapted to the luminance of the nighttime earth as seen from orbit.

The luminous flux entering the operator's eye from an optical beacon on the ground is the product of illuminance from the beacon at the observer's location and the instantaneous area of the pupil of his eye. Pupil size will be assumed to remain constant during S191 observations. With the preceding assumptions, visibility of the beacon will be determined by its illuminance at the observer's location.

A comprehensive study of visibility thresholds based on brightness discrimination was made at the L. C. Tiffany Foundation during the Second World War (Reference 11). Test subjects were young women, 19 to 26 years of age, whose visual acuity in each eye and in both eyes was nearly 20/20 without refractive correction. Visual stimuli were uniformly luminous circular disks of various diameters presented against a uniform background luminance. Subjects were adapted to the background luminance prior to test sessions. Exposure durations of six to fifteen seconds were used. Figure 1 reproduces a portion of the Tiffany data for a stimulus which constituted a "point source" for the test subjects.

The data shown in that Figure can be used to calculate the illuminance ($\hat{E}$) at orbital altitude required for an optical beacon to be visible to an astronaut operating Experiment S191.

As noted above, individual stimuli in the Tiffany tests were uniformly luminous. Test subjects viewed the stimuli from a direction approximately normal to the plane on which they were displayed. Therefore the luminous intensity ($\hat{I}_d$) of a stimulus perceived by observers at the threshold of detection is represented by



NOTE: THE CURVE SHOWN IS BASED ON A 50% PROBABILITY OF DETECTION

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* 1 MILLILAMBERT = 3.18 LUMENS/(STERADIAN-METER^2)

FIGURE 1 - THRESHOLD CONTRAST AS A FUNCTION OF BACKGROUND BRIGHTNESS FOR A STIMULUS SUBTENDING AN ANGULAR DIAMETER OF 0.595 ARCMINUTES (REFERENCE 11)

$$\hat{I}_d = aL_s \ , \qquad (4.2\text{-}1)$$

where a is the area of the stimulus and L_s is the perceived luminance of the stimulus.

Let ω_1 be the solid angle subtended by the test stimulus whose angular diameter was 0.595 arcminutes ($\omega_1 = 2.36 \times 10^{-8}$ steradians). Let d represent the distance between test subject and stimulus. Then, since $d^2 >> a$,

$$a = \omega_1 d^2 \ . \qquad (4.2\text{-}2)$$

Combining Equations (4.2-1) and (4.2-2), we have

$$\hat{I}_d = \omega_1 d^2 L_s \ . \qquad (4.2\text{-}3)$$

From the definition of threshold contrast (Section 4.1),

$$L_s = L_B \ (1 + C_T) \ . \qquad (4.2\text{-}4)$$

Multiplying Equation (4.2-4) by $\omega_1 d^2$, and substituting Equation (4.2-3) into the result yields

$$\hat{I}_d = \omega_1 d^2 \ L_B \ (1 + C_T) \ . \qquad (4.2\text{-}5)$$

From Equations (4.1-2 and (4.2-5), we have

$$\hat{E} = \omega_1 L_B \ (1 + C_T) \ , \tag{4.2-6}$$

where $\hat{E}$ is the threshold illuminance for a point source viewed against a background luminance L_B, C_T being given by Figure 1.

Equation (4.2-6) applies to a steady (non-flashing) light source. All other things being equal, a rapidly flashing light must, to be visible, have a higher instantaneous intensity than a steady light. The instantaneous intensity ($\hat{I}_1$) of a flashing light at the threshold of visibility is related to the threshold intensity ($\hat{I}_2$) of a steady source by Talbot's Law (Reference 8):

$$\hat{I}_1 = \hat{I}_2 \ \left(\frac{0.21 + \Delta t}{\Delta t}\right) \ , \tag{4.2-7}$$

where Δt is the flash duration in seconds. If $\hat{I}_2$ is identified with $\hat{I}_d$ in Equation (4.2-5), Equation (4.2-6) becomes

$$\hat{E} = \left(\frac{0.21 + \Delta t}{\Delta t}\right) \ \omega_1 L_B \ (1 + C_T) \ , \tag{4.2-8}$$

where $\hat{E}$ is now the instantaneous illuminance of a flashing light at the threshold of visibility.

Thus far it has been implicitly assumed that light passes unattenuated through the air between source and observer. This assumption is valid for laboratory tests where the light path is short. However, for an astronaut in orbit viewing a beacon on the earth, the light path traverses the entire depth of the atmosphere. It will therefore be necessary to take into account the transmissivity (T) of the medium between source and observer.*

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*Transmissivity can be defined as the fraction of luminous flux remaining in a light ray after passing through a given medium.

A background of actual luminance L_B' will, when viewed through a medium having transmissivity T, appear to have a luminance L_B given by

$$L_B = TL_B' \, . \tag{4.2-9}$$

It follows from Equation (4.1-2) that the illuminance E perceived by an observer at a distance ρ from a point source emitting light of intensity I is

$$E = \frac{TI}{\rho^2} \, , \tag{4.2-10}$$

where T is the transmissivity of the medium between source and observer. Let $\hat{I}_\rho$ be the threshold intensity for an observer at distance ρ. Applying Equation (4.2-10) at the threshold of visibility and substituting it, together with Equation (4.2-9) into Equation (4.2-8) results in

$$\hat{I}_\rho = \rho^2 \left(\frac{0.21 + \Delta t}{\Delta t}\right) \omega_1 L_B' \left[1 + C_T \,(TL_B')\right] \, , \tag{4.2-11}$$

where threshold contrast, C_T, has been written as $C_T(TL_B')$ to emphasize that it is the threshold contrast value corresponding to a perceived background luminance $L_B = TL_B'$, as given by Figure 1.

Equation (4.2-11) can be used to determine the threshold intensity of a flashing beacon viewed from orbit if ρ is taken to be the distance from beacon to spacecraft and T is the atmospheric transmissivity between beacon and spacecraft.

Let ζ represent the angle between local vertical at the beacon's location and a straight line joining beacon to spacecraft. ζ will be referred to as the zenith angle. T varies with zenith angle in accordance with the following relation (Reference 12):

$$T = e^{-\bar{\beta}\sec\zeta} . \qquad (4.2\text{-}12)$$

The transmissivity through clear air for starlight viewed at the zenith from sea level varies from ~ 0.78 to ~ 0.83 (Reference 12). Assuming an intermediate value of T=0.8 for $\zeta=0$, Equation (4.2-9) becomes

$$T = e^{-0.223\sec\zeta} . \qquad (4.2\text{-}13)$$

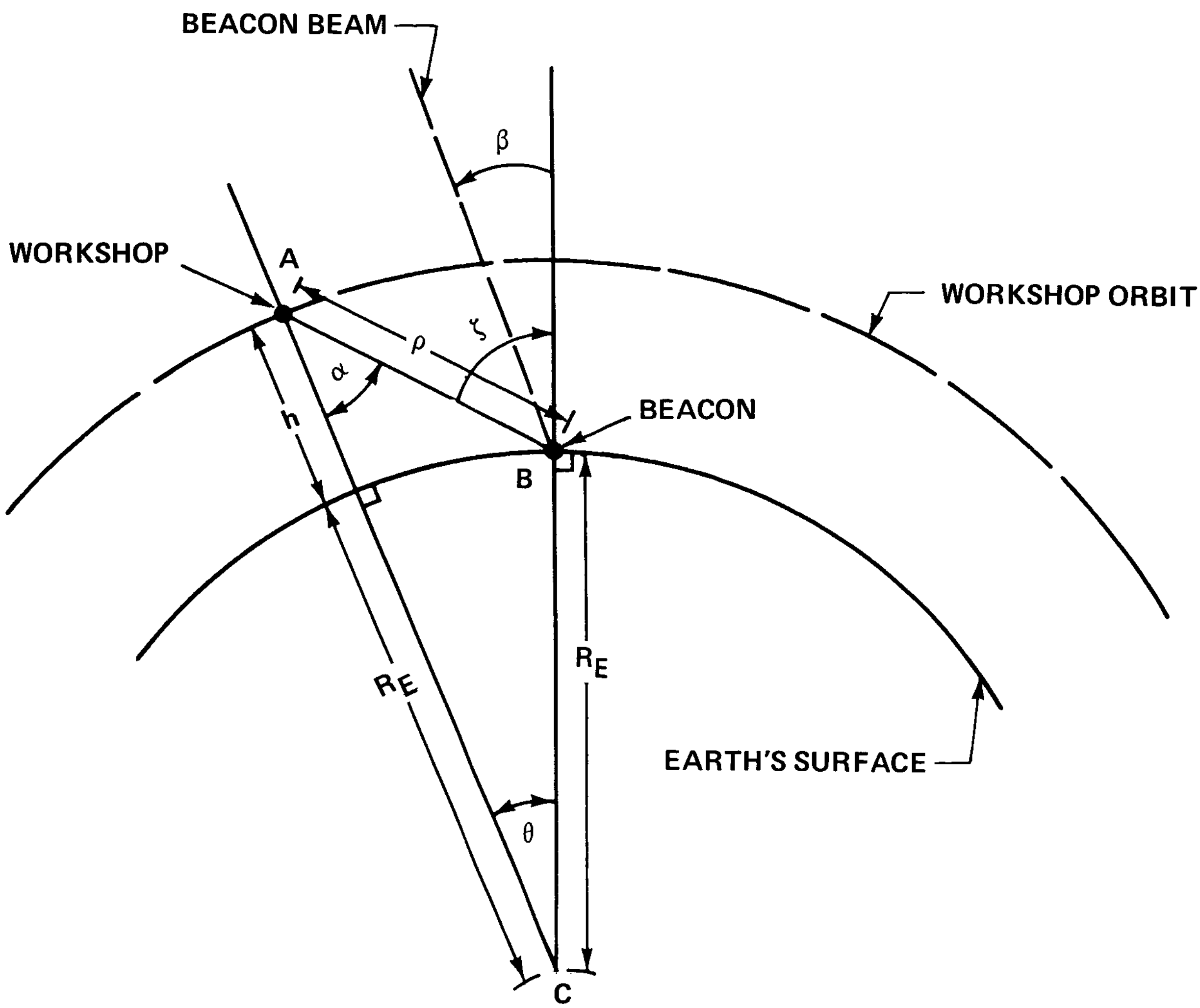
The distance ρ is also a function of ζ. The law of cosines, applied to triangle ABC of Figure 2, yields

$$\rho = -R_e \cos\zeta + \sqrt{(R_e + h)^2 - R_e^2 \sin^2\zeta} , \qquad (4.2\text{-}14)$$

where R_e is the radius of the earth and h is the Workshop's circular orbital altitude.

The curve shown in Figure 1 is based on a 50% probability of detection. To be of practical usefulness, an S191 target marker would require a substantially higher detection probability. For the purposes of this study, a 90% probability of detection is assumed to be adequate. Threshold contrast values for a 90% detection probability are 1.62 times the 50% detection probability values of Figure 1 (Reference 11).

To summarize thus far, the minimum luminous intensity ($\hat{I}_\rho$) of a flashing beacon required for visibility from orbit by the naked eye with 90% probability of detection is, from Equation 4.2.11,



NOTE: R_E = RADIUS OF EARTH

h = CIRCULAR ORBITAL ALTITUDE OF WORKSHOP

ζ = ZENITH ANGLE

FIGURE 2 - GEOMETRICAL RELATIONSHIP OF ORBITING WORKSHOP AND BEACON LOCATION ON THE GROUND

$$\hat{I}_\rho = \rho^2 \left(\frac{0.21 + \Delta t}{\Delta t}\right) \omega_1 L_B' \left[1 + 1.62\, C_T\, (TL_B')\right] , \qquad (4.2\text{-}15)$$

where

$\omega_1 = 2.36 \times 10^{-8}$

Δt = flash duration in seconds

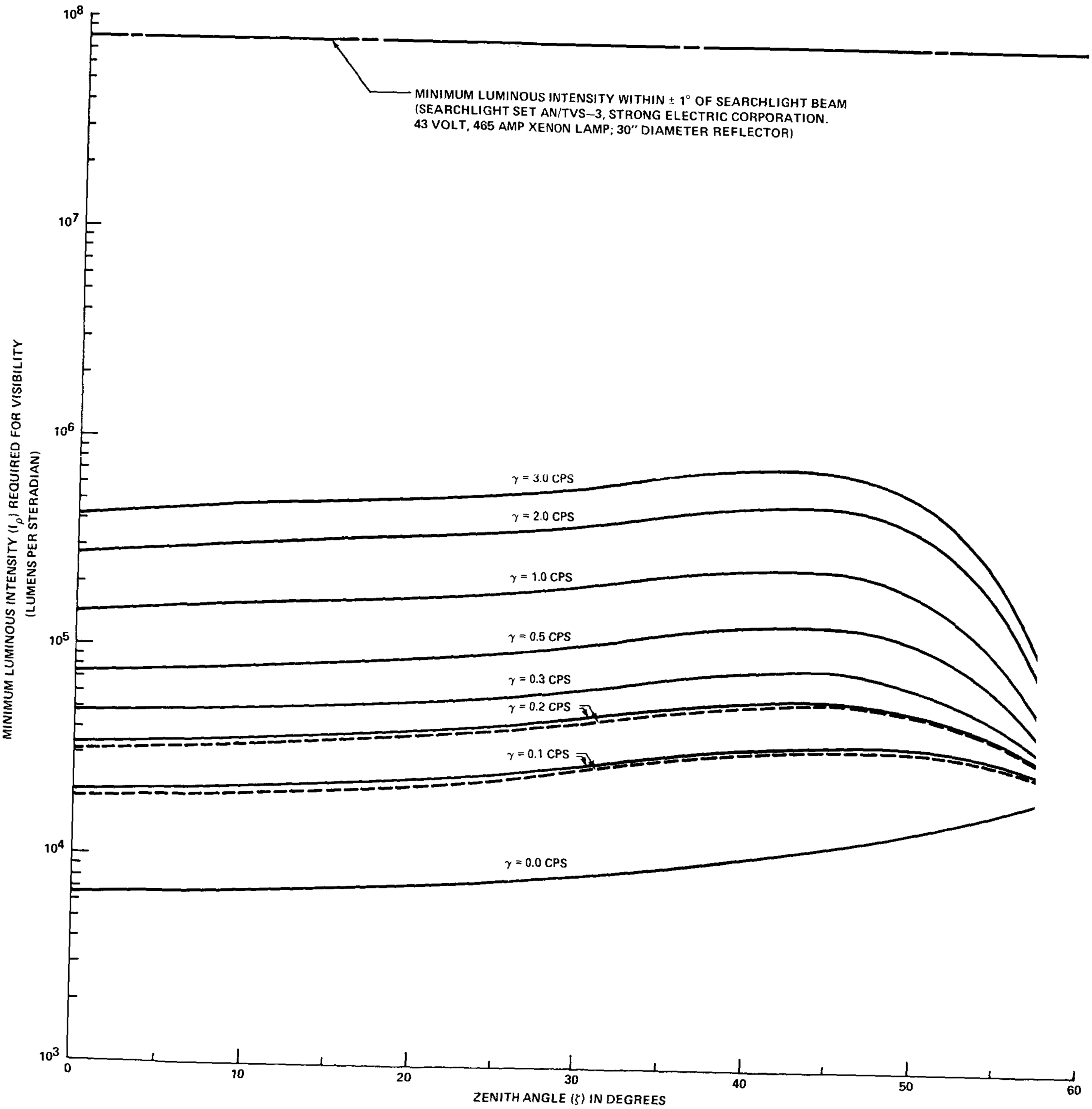
L_B' = luminance of the earth near the beacon's location

C_T = threshold contrast from Figure 1

and where T, ρ are given as functions of zenith angle by Equations (4.2-13), (4.2-14), respectively.

A quantitative description of the effects of the S191 Viewfinder/Tracking System (V/TS) optics on the visibility of a ground beacon requires more information on the V/TS telescope than is available at the present time. However, a few qualitative observations can be made. An optical instrument cannot make an extended object appear to have a greater luminance than it actually has (Reference 13). Assuming the V/TS telescope is designed so that the pupil of the observer's eye is the aperture stop of the system, the earth will appear nearly as bright through the V/TS as it would to the naked eye, the difference being attributable to the transmissivity of the V/TS optics.

An S191 optical beacon on the ground will be a point source when viewed from orbit. That source will appear "brighter" through the V/TS than to a naked eye in the same location: the beacon illuminance reaching the eye through the V/TS will be greater than the illuminance reaching a naked eye at the same location. That is, the telescope has greater light-gathering capability than the observer's eye, the telescope having a larger entrance aperture. Since the background brightness of the earth will be relatively unaltered by the V/TS, the enhanced illuminance of the beacon will render it more easily visible through the V/TS than with the naked eye. Equation (4.2-15) will therefore give a conservative estimate of the minimum luminous intensity required for an S191 beacon. Equation (4.2-15) is presented graphically in Figure 3, based on values of Δt derived below and shown in Figure 4. A discussion of Figure 3 is presented in Section 6.0.



NOTE: CURVES APPLY TO THE NIGHT SIDE OF THE EARTH, ILLUMINATED BY A FULL MOON
SEARCHLIGHT BEAM OSCILLATION IS $\beta \approx 0.34 \pm 0.69$ SIN $(2\pi\gamma t)$ RADIANS
SOLID (———) AND DASHED (– – –) CURVES ARE BASED ON POSITIVE AND NEGATIVE VALUES OF $\dot{\beta}$ RESPECTIVELY

FIGURE 3 - COMPARISON OF REQUIRED AND AVAILABLE LUMINOUS INTENSITIES FOR AN S191 OPTICAL TARGET MARKER

4.3 Flash Duration and Flashing Frequency for a Searchlight Beacon

The beacon concept described in Section 3.0 employs a searchlight beam swung in a vertical arc such that it would appear as a flashing light to an astronaut operating Experiment S191. The duration of a flash, Δt, is simply the time during which the spacecraft is within the rotating searchlight beam. Defining the divergence, γ, of the beam as the total angle centered on the beam's axis at which the beam's luminous intensity has fallen off to 10% of its maximum (centerline) value, the beam can for simplicity be considered to lie entirely within the cone defined by its divergence. As can be seen from Figure 2, the angular velocity of the beam relative to the spacecraft is $\dot{\zeta} + \dot{\beta}$. If γ is small and the relative angular velocity between searchlight beam and spacecraft is large,

$$\Delta t(\zeta) = \frac{\gamma}{|\dot{\zeta} + \dot{\beta}|} , \tag{4.3-1}$$

where $\dot{\zeta}$ is evaluated at ζ and $\dot{\beta}$ is evaluated at $\beta = \zeta$. Referring again to Figure 2 it is apparent that $\zeta = \Theta + \alpha$; therefore,

$$\dot{\zeta} = \dot{\Theta} + \dot{\alpha} , \tag{4.3-2}$$

where the dot, as usual, denotes differentiation with respect to time. Applying the law of sines to triangle ABC of Figure 2,

$$\sin \alpha = \frac{R_e}{R_e+h} \sin \zeta , \tag{4.3-3}$$

which, when differentiated with respect to time, yields

$$\dot{\alpha} = \frac{R_e \; (\cos \zeta)(\dot{\zeta})}{(R_e+h) \; \cos \alpha} \quad . \qquad (4.3\text{-}4)$$

Applying the law of cosines to triangle ABC,

$$\cos \alpha = \frac{\rho^2 + (R_e+h)^2 - R_e^2}{2\rho \; (R_e+h)} \quad . \qquad (4.3\text{-}5)$$

Substituting Equation (4.3-5) into Equation (4.3-4) and substituting the resulting relation into Equation (4.3-2) yields

$$\dot{\zeta} = \frac{\dot{\theta}}{\left\{1 - \frac{2 \; R_e \; \rho \; \cos \zeta}{\left[\rho^2 + (R_e+h)^2 - R_e^2\right]}\right\}} \quad . \qquad (4.3\text{-}6)$$

Substituting Equation (4.2-14) into Equation (4.3-6) gives the following result:

$$\dot{\zeta} = \frac{\dot{\theta}\chi^{1/2}}{\chi^{1/2} - R_e \; \cos \zeta} \quad , \qquad (4.3\text{-}7)$$

where $\chi \equiv (R_e+h)^2 - R_e^2 \sin^2 \zeta$.

The range of zenith angles for which a beacon on the ground will be within the S191 field-of-view is limited by the local-vertical spacecraft attitude used during EREP passes and by the V/TS itself. The V/TS's maximum instantaneous optical field-of-view (IFOV) is 17° (Reference 14). The

IFOV's centerline can be rotated as much as 45° forward of the Workshop's local vertical and 10° aft of that line (Reference 2). The "leading edge" of the overall V/TS optical field-of-view is therefore defined by $\alpha = 45°+17°/2=53.5°$, the "trailing edge" being $10°+17°/2=18.5°$ aft of the Workshop's local vertical. From Equation (4.3-3) the range of zenith angles within which the beacon will be visible through the V/TS is $-20° \leqslant \zeta \leqslant 59°$, for a Workshop altitude of 235. nautical miles. Therefore the arc through which the searchlight beam must be swung for it to be seen by an S191 operator throughout a given pass is $-20° \leqslant \beta \leqslant 59°$ or $\beta = 0.34$ radians ± 0.69 radians.

It is assumed that the searchlight beam will be swung such that β varies sinusoidally with time, i.e.

$$\beta = \hat{\beta} + M \sin (2\pi\gamma t) \ , \tag{4.3-8}$$

where $\hat{\beta} = 0.34$ radians, $M = 0.69$ radians, γ is the frequency of the light beam's oscillation in cycles/sec, and t is time in seconds. Differentiating Equation (4.3-8) with respect to time and combining the result with Equation (4.3-8) yields

$$\dot{\beta} = 2\pi\gamma \ M \cos \left\{ \sin^{-1} \left[\frac{\beta - \hat{\beta}}{M} \right] \right\}. \tag{4.3-9}$$

$\dot{\beta}$ is a double valued function of β. Equation (4.3-9) can be rewritten as

$$\dot{\beta} = \pm 2\pi\gamma \sqrt{M^2 - (\beta - \hat{\beta})^2} \tag{4.3-10}$$

Substituting Equations (4.3-7) and (4.3.10) into Equation (4.3-1) leads to

$$\Delta t = \frac{\gamma}{\left| \frac{\dot{\Theta}\chi^{1/2}}{\chi^{1/2} - R_e \cos \zeta} \pm 2\pi\gamma \sqrt{M^2 - (\zeta - \hat{\beta})^2} \right|}, \tag{4.3-11}$$

where, as before, $\chi \equiv (R_e+h)^2 - R_e^2 \sin^2 \zeta$ and $\dot{\Theta}$ is the angular velocity of the Workshop relative to the earth's center. For a circular orbit,

$$\dot{\Theta} = \frac{\mu^{1/2}}{(R_e+h)^{3/2}}, \tag{4.3-12}$$

where μ is the gravitational constant 3.986×10^{14} meters^3/sec^2. At an altitude of 235. nautical miles, $\dot{\Theta} = 1.12 \times 10^{-3} \frac{\text{radians}}{\text{second}}$.* Equation (4.3-11) is shown graphically in Figure 4 for eight values of γ ranging from 0. to 3. cycles per second (CPS).

It should be noted that, in general, two flashes of light will be seen by an S191 operator during each cycle of the

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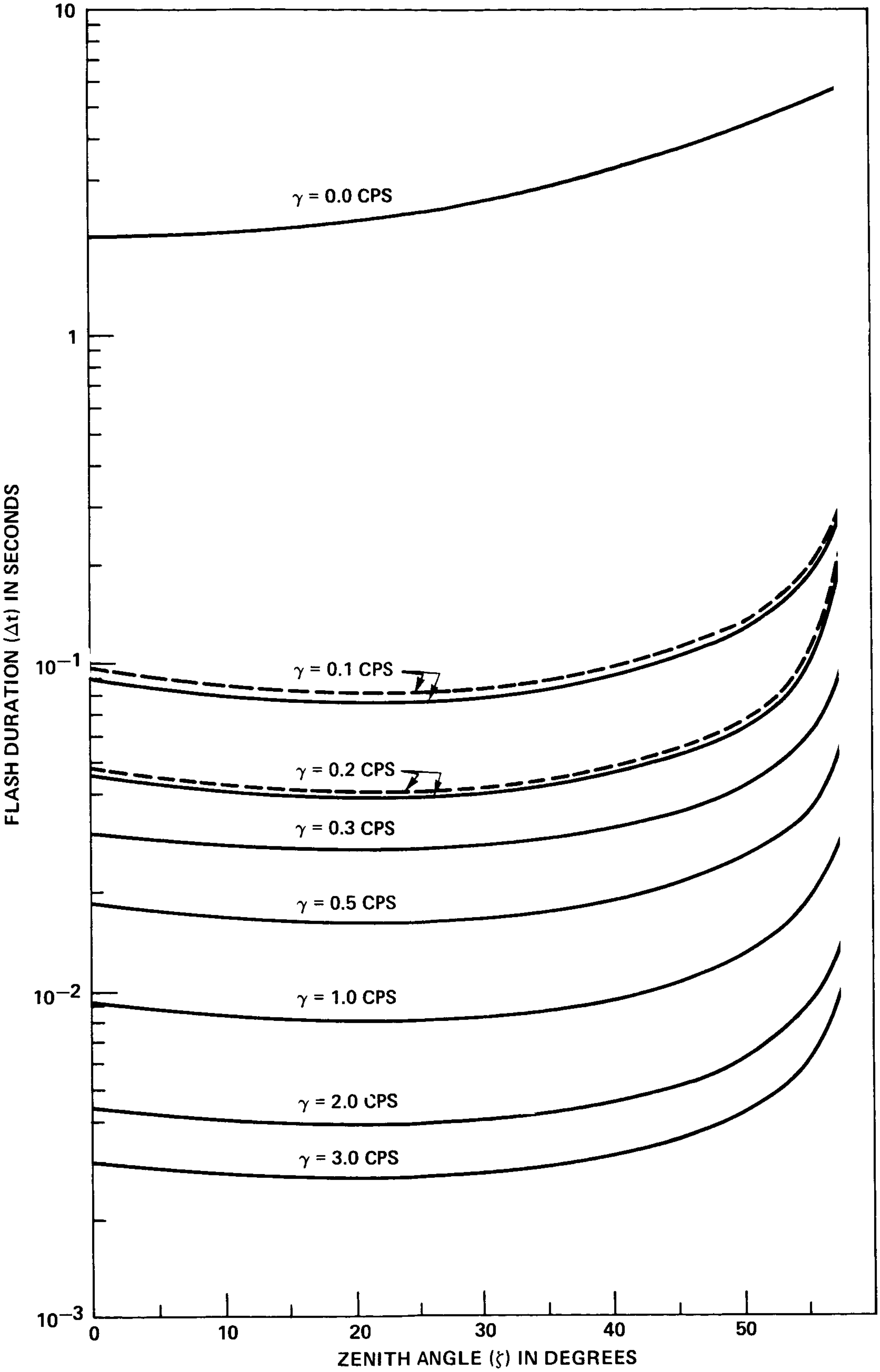
*At this point it is of interest to note that the duration (T) from visual acquisition of an S191 target until the Workshop passes over it is $\Theta'/\dot{\Theta}$, where Θ' is the value of Θ at acquisition. The values of ζ and α at acquisition have been shown above to be 59° and 53.5° respectively. Since $\Theta = \zeta - \alpha$, $\Theta' = 59° - 53.5° = 5.5°$ or 0.09 radians. Therefore, $T = \Theta'/\dot{\Theta} = 0.096/(1.12 \times 10^{-3}) = 85.6$ seconds.



NOTE: SOLID AND DASHED LINES DENOTE Δt FOR POSITIVE AND NEGATIVE VALUES OF $\dot{\beta}$, RESPECTIVELY

γ = FREQUENCY OF SEARCHLIGHT OSCILLATION

SEARCHLIGHT BEAM DIVERGENCE = 2°

RANGE OF SEARCHLIGHT OSCILLATION = 0.34 ± 0.69 RADIANS FROM LOCAL VERTICAL

FIGURE 4 - FLASH DURATION VS ZENITH ANGLE

searchlight beacon's oscillation. Having previously defined γ as the light beam's frequency of oscillation in cycles per second, the average flash rate, ϕ, seen from orbit is

$$\phi = 2\gamma \ , \tag{4.3-13}$$

where ϕ is measured in flashes per second. The S191 operator will see a series of pairs of flashes as the beacon comes into view; the interval between flashes of a given pair will gradually increase as the spacecraft subpoint approaches the beacon, reaching a maximum at $\zeta = 19.5°$.

5.0 Searchlight Capabilities

A variety of commercially available searchlights are manufactured in this country (Reference 10). A detailed survey of their capabilities would extend the scope of this memorandum considerably. It is, however, necessary to demonstrate the existence of a searchlight capable of meeting the requirements for an S191 beacon in order to establish the feasibility of the beacon concept proposed in this study. Therefore, for the purposes of this report, attention will be focused on one readily available searchlight: the AN/TVS-3 set* used by NASA at KSC for launch pad illumination and also used extensively by the U.S. Army. KSC presently uses fifty of these searchlights. An additional 28 searchlights of the same type have been requested to support Skylab launch operations (Reference 15).

Each of these searchlight units contains a 43 volt 465 ampere xenon lamp mounted within a 30" diameter reflector, thereby providing a luminous intensity of at least 8×10^8 lumens/steradian along the centerline of the projected light beam, with a divergence γ of 2° (Reference 16). The lamp/reflector module is gimballed in azimuth and elevation relative to its wheel-mounted base; rotation in azimuth is available over a range of ±270°, in elevation over a range of -22° to +100° from the horizontal (Reference 16). Only manual control of beam pointing is presently possible. However, it is anticipated that a capability for a motor-driven sinusoidal sweep of the type assumed in this study would not be difficult to incorporate (Reference 15).

The minimum luminous intensity of the AN/TVS-3 searchlight within ±1° of its beam's centerline is plotted in Figure 3. This conservatively represents the searchlight's capability since the minimum intensity is only ten percent of peak intensity.

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*Manufactured by the Strong Electric Corporation, Toledo, Ohio.

6.0 Discussion of Results

Figure 3 graphically illustrates the feasibility of the beacon concept proposed in this memorandum. For searchlight beam oscillations as high as 3 cycles per second the luminous intensity of the beacon required for visibility from orbit does not exceed 8×10^5 lumens/steradian throughout the range of zenith angles for which the target will be in line-of-sight contact with the V/TS. Searchlight oscillation frequencies of practical interest will probably be in the range of $\sim$0.1 to $\sim$0.5 cycles per second which corresponds to average intervals between flashes of 1. to 5. seconds. (Average rates greater than one flash per second might needlessly induce undesirable vibration effects in the searchlight mount.) Therefore, it is likely that the maximum luminous intensity required for a searchlight beacon is $\sim 1.2 \times 10^5$ lumens/steradian. The AN/TVS-3 searchlight described previously will provide a minimum intensity nearly three orders of magnitude greater than the required intensity.

7.0 Acknowledgment

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